Low-Frequency Sheath Instability in a Non-Maxwellian Plasma with Energetic Ions

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Spontaneous low-frequency oscillations have been observed in the circuit of a positively biased electrode when the ambient nonuniform plasma is irradiated by a microwave pulse of short duration, which is approximately equal to the ion-plasma period. The instability with its characteristic frequency below the ion-plasma frequency is driven by an accelerated ion component interacting with the sheath of the electrode. A qualitative model of the instability is suggested.

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Sheath-plasma instabilities are of great interest for fundamental plasma physics as a basic plasma property and for different applications, such as plasma diagnostic techniques [1], plasma diodes [2] and discharges [3–5], antennas in plasmas [6,7], and current systems in space [8]. The high-frequency sheath-plasma instability is a well-known process [7] which occurs in the sheath of a positively biased electrode due to the finite electron transition time through the sheath. Low-frequency sheath processes can also significantly affect the probe characteristics under some specific experimental conditions. A feature of current overshoot in pulsed probe measurements [9] occurs near the plasma potential for positive voltage pulses due to the inertia of ions in the sheath; similar time-dependent probe measurements in a large magnetoplasma [7] exhibit not only current overshoots but also low-frequency relaxation oscillations due to the current-driven instability. Low-frequency instability of a hollow-cathode discharge effecting a collapse of the cathode sheath voltage has been observed [3] and used to develop a new sort of high-power pulsed rf generators [4]. Spontaneous low-frequency dynatron oscillations caused by secondary electron emission have been detected when an energetic electron beam is incident on an electrode [10]. Low-frequency noise excited by two counterstreaming ion flows has been found in the presheath of a negatively biased mesh probe [11].

In this Letter we report the observation of a low-frequency sheath-plasma instability that occurs at the electron saturation current of a disc probe in the presence of energetic ion component. The observed instability differs from the previously reported processes [3–7,9–11] and is characterized by the following features: (i) oscillations in the probe current occur only when the probe is biased positively with respect to the plasma potential; (ii) the instability is driven by a flux of suprathermal ions; (iii) the instability amplitude exhibits saturation when the energetic ion component is reflected inside the sheath and cannot reach the probe surface. The instability is not only of substantial interest as a fundamental phenomenon but also may arise in different plasma applications when a positively biased electrode interacts with a plasma containing a group of accelerated ions. Such applications include, for example, tether systems incident by energetic ions inherently existing in space plasmas. Let us also notice that the instability may occur not only in the sheath of an electrode but also in plasma double layers, both in laboratory and space plasmas, if an energetic ion component enters into a double layer from the lower-potential side.

In the present experiment, the high-energy ion component has been produced by resonant absorption of a short microwave pulse (the pulse duration is in the order of an ion-plasma period). It is known that the resonant absorption process can cause the ion acceleration [12] due to the ambipolar electric field, which is a result of the electron expulsion from the resonant region. Indeed, the incident electromagnetic wave is greatly enhanced in the region where its frequency is equal to the plasma frequency. This highly localized electric field produces a ponderomotive force which pushes plasma electrons down the field gradient. Accelerated electrons pull the ions by means of ambipolar electric field producing ion acceleration. Resulting plasma density perturbation propagates down the density gradient as a nonlinear ion-wave (hereinafter referred as an ion-wave streamer) with a precursor consisted of energetic ions. The above model is confirmed by our experimental observations but the exact identification of the ion acceleration process is outside the scope of this Letter.

The experiments (see Fig. 1) are performed in a large (diameter 60 cm, length 1 m) laboratory plasma device with multipol magnetic confinement system. A nonuniform plasma column with maximum density $n_e \approx 2 \times 10^{11}$ cm^{-3}, electron temperature $T_e \approx 2$ eV, ion temperature $T_i \approx T_e/10$ is produced at argon gas pressure $p = 4 \times 10^{-4}$ Torr with a pulsed dc discharge (pulse duration $\tau_{\rm dis} = 2.5$ ms, repetition rate $f_{\rm dis} = 10$ Hz) using a tungsten filament cathode. The typical density gradient scale lengths in the axial direction (z direction) and in the radial (r direction) are, respectively, $L_z = (\partial \ln n/\partial z)^{-1} \approx 100$ cm and $L_r = (\partial \ln n/\partial r)^{-1} \approx 50$ cm.

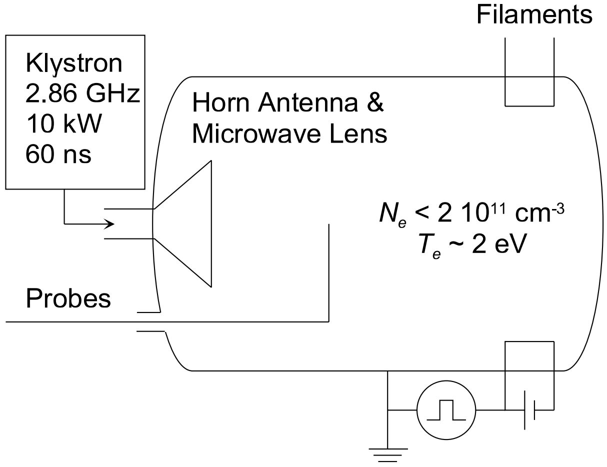

FIG. 1. Schematic view of the experimental setup.

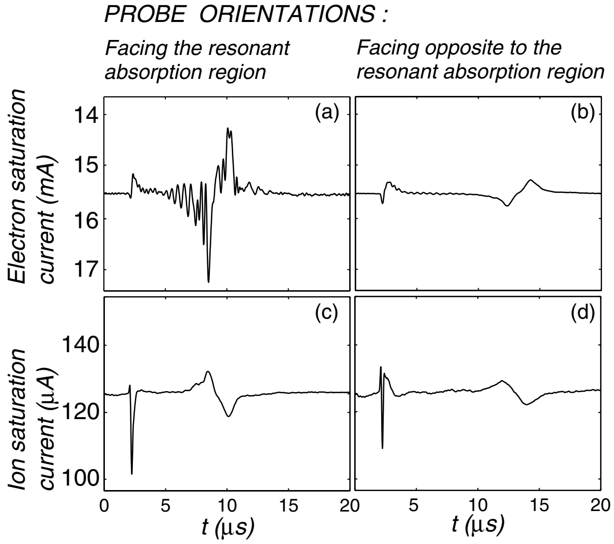

FIG. 2. Probe currents vs time at different probe orientations. [(a),(b)]: the electron saturation current (at $V = 50$ V) when the probe facing the resonant absorption region (a) and facing opposite to the resonant absorption region (b). [(c),(d)]: the ion saturation current (at $V = -70$ V) when the probe facing the resonant absorption region (c) and facing opposite to the resonant absorption region (d). The probe is located at 5 cm below the resonant region. Microwave pulse parameters: $P = 10$ kW, $\tau = 50$ ns.

A p-polarized microwave pulse with frequency $f = \omega/2\pi = 2.86$ GHz and a maximum power of 10 kW is produced by a klystron and is radiated into the plasma volume from a high gain horn antenna located at the lower-density side of the plasma chamber. The pulse width of the order of 60 ns at a full width at half maximum is approximately equal to the ion-plasma period. The critical density layer ($\omega = \omega_p$, where ω_p is the plasma frequency) is located near the center of the chamber. Diagnostics used in the experiment include two oppositely directed disc probes measuring the ambient plasma density and its fluctuations, a microwave resonator probe [13], a short dipole antenna, and an electrostatic energy analyzer oriented to the overdense plasma to measure the particles accelerated toward the lower-density side.

When the laboratory plasma was irradiated with a 10 kW, 50 ns microwave pulse, a flux of energetic ions along with a nonlinear ion-wave propagated downward the density gradient. In the vicinity of the resonant region, the ion beam density was about 0.05 of the ambient plasma density N_e, while the amplitude of the ion wave was about 0.1 of N_e. Figure 2 shows a set of typical oscillograms of the electron and the ion saturation currents for two oppositely directed probes (both probes are 2 mm diam). The probes have been placed at the lower-density side of the resonant absorption region at a distance $\Delta z \approx 5$ cm from the resonance point ($\Delta z = 0$ corresponds to the resonant absorption point; increasing Δz corresponds to decreasing the plasma density). One can notice an ion-wave streamer (propagating down the density gradient), clearly in Figs. 2(b)–2(d). However, Fig. 2(a) displays not only the streamer, but also high-frequency oscillations with characteristic period $\tau_{\rm osc} \approx 0.3$ μs, which occur in the electron saturation current of a probe facing the resonance region. This Letter is aimed toward uncovering the nature of these oscillations. Comparing Fig. 2(a) and Figs. 2(b)–2(d), one can conclude that the oscillations do not correspond to the real plasma density perturbations as the same phenomena are not detected when probe is biased in the ion saturation region [Fig. 2(c)] as well as by the probe facing opposite to the resonance region [Fig. 2(b) and 2(d)]. We believe that the oscillations in the electron saturation current are due to a sheath instability. The instability has been observed for three probe diameters D (1, 2, 15 mm). Characteristics of the instability have been found to be approximately the same for all probe diameters. Thus in this Letter we will concentrate on the measurements by the probe with $D = 2$ mm.

The nature of the high-frequency oscillations has also been examined with a microwave resonator probe [13]. A quarter-wavelength U-shaped high-quality ($Q \approx 170$) resonator [Fig. 3(a)] exhibits a resonance at $f_{\rm res} \approx 4.88$ GHz in vacuum and $f^*_{\rm res} \approx 5.28$ GHz in plasma near the resonance region. Measurements have been performed when the signal frequency is tuned to the slope of the resonance curve ($f \approx 5.32$ GHz) such that small shifts of the resonant frequency due to plasma density perturbations produce approximately proportional variations of the amplitude of the probe output signal. Measurements by the resonator probe presented in Fig. 3(b) are similar to ones presented in Figs. 2(b)–2(d) and do not display the oscillations observed in Fig. 2(a), although the probe time response is approximately $\tau \approx Q/f_{\rm res} \approx 30$ ns which is much shorter than the characteristic period of these oscillations.

The above results clearly demonstrate that the oscillations of the electron saturation current are not due to

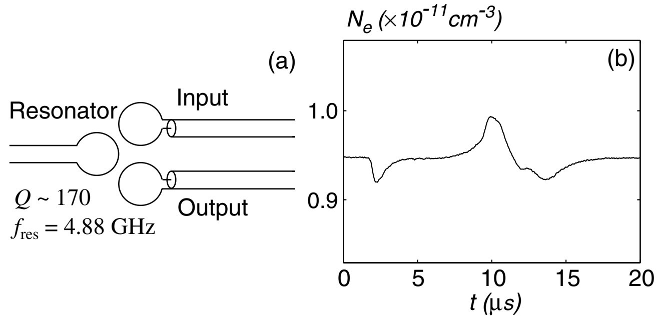

FIG. 3. Measurements of plasma density perturbations by using the microwave resonator probe. (a): Schematic view of the probe. (b): Temporal behavior of the probe output signal at $f = 5.32$ GHz calibrated in terms of plasma density. Probe parameters: resonance frequency in vacuum $f_{\text{res}} = 4.88$ GHz, $Q \approx 170$. The probe is located at 5 cm below the resonant region.

plasma density fluctuations but are related to a sheath instability. The instability occurs only when the probe is biased positively with respect to the plasma potential, as it is displayed in Fig. 4 where the ratio $I_{\text{osc}}/I_{\text{dc}}$ is plotted vs the probe bias voltage. Here, the plasma potential is indicated as V_{pl}. One can see that the relative amplitude of the observed oscillations does not remain constant (as it should be for the case of real density perturbations) but exhibits a threshold, growth, and saturation, i.e., typical behavior for instabilities [7].

The instability has been observed only from the lower-density side of the resonant region, when the disc probe surface is incident by the energetic flux of plasma particles produced by the resonant absorption process. The nature of the instability is related to the energetic ion flux, as it is evidenced in Fig. 5, which presents the temporal evolution of the electron saturation current at different distances Δz between the probe and the resonant region. One can see that the instability becomes well separated in time from the microwave pulse as Δz increases. At larger distances [Figs. 5(d) and 5(e)] one can observe that the instability is temporally limited within a few microseconds before the ion-wave streamer reaches the probe. The streamer, which is a nonlinear ion perturbation, has been found to travel down the density gradient with approximately twice the sound speed c_s. Thus the measurements presented in Fig. 5 prove that the instability is associated with energetic ions propagating toward the lower-density side with velocities $v_b \sim (3\text{–}5)c_s$.

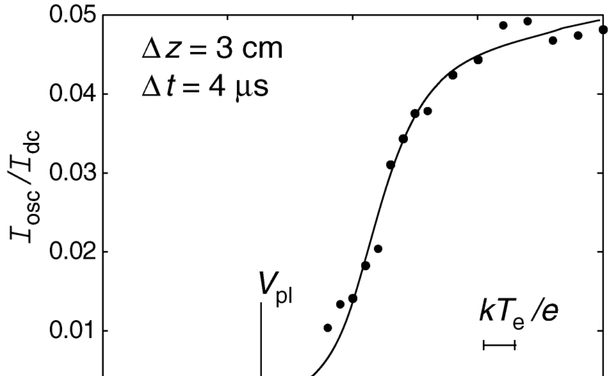

FIG. 4. Relative instability amplitude versus dc bias voltage showing that the instability occurs only when the probe is biased positively with respect to the plasma. The probe is located $\Delta z = 3$ cm below the resonant region. Instability amplitude is measured at $\Delta t = 4$ μs after finishing the microwave pulse. Plasma potential and electron temperature are indicated.

A typical energy spectrum of the accelerated ion component is displayed in Fig. 6 showing the presence of energetic ions with energies up to 17 V, which is approximately 1 order of magnitude larger than kT_e. These measurements were performed with an ion-energy analyzer which discriminates against ions below a certain energy by a positive potential applied to the collector. Two grids are placed in front of the collector: the outer one is left at floating potential in order to reduce disturbances of analyzer on the ambient plasma, the inner one is biased negatively in order to reflect plasma electrons. The

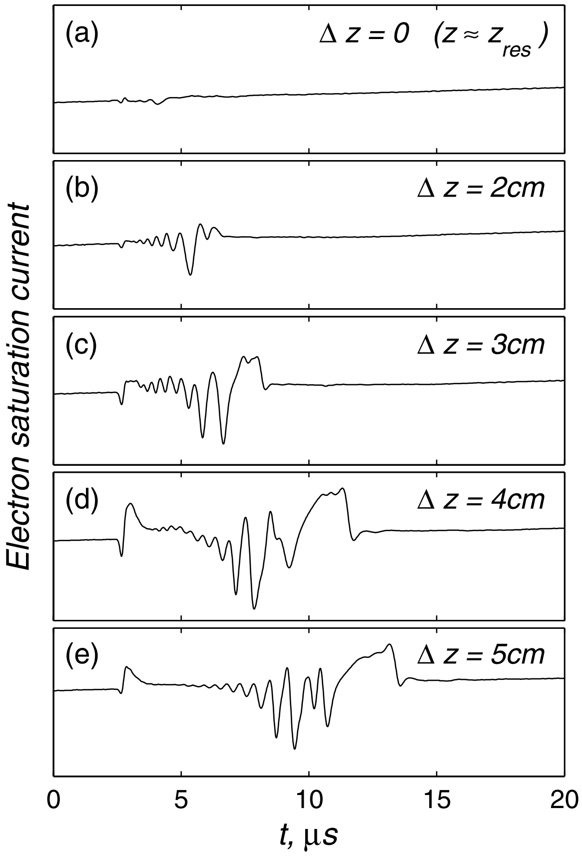

FIG. 5. Electron saturation current ($V = 50$ V) at different distances from the resonance absorption region showing that the instability is driven by the energetic ion flux produced by the resonant absorption process.

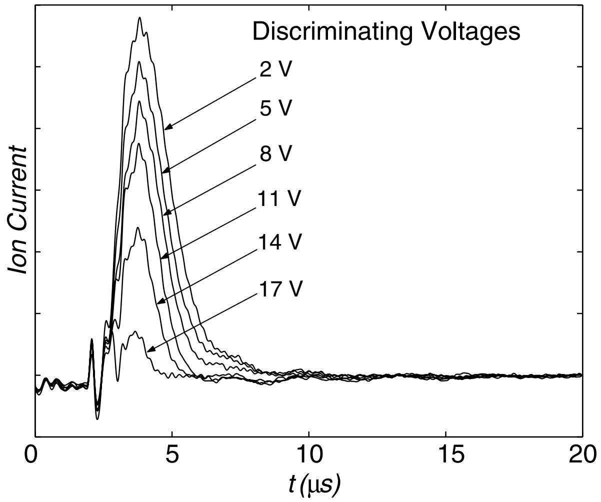

FIG. 6. Temporal behavior of ions accelerated towards the lower-density side measured by energy analyzer at different potentials applied to the discriminating grid. The analyzer is located 3 cm below the resonant region.

analyzer is located at approximately 3 cm down the density gradient from the resonant region. One can see that the resonant absorption of a short microwave pulse produces a group of accelerated ions with a wide range of ion velocities. As this ion structure travels down the density gradient the peak disperses and fast ion components reach the probe significantly earlier than the ion-wave streamer [compare with Fig. 5(e)].

Summarizing the above measurements, the observed low-frequency oscillations of the electron saturation current do not represent plasma density perturbations but are due to an instability of an electron-rich sheath driven by an energetic ion beam component.

We can suggest a qualitative model of the instability. Consider a positively biased probe immersed into a plasma with an ion beam. If the probe potential U_0 is greater than the ion beam energy U_b, the ion beam is reflected inside the electron-rich sheath. Near the reflection point the density of beam ions increases manifolds and diminish, the total negative space charge of the sheath. As a result, an overshoot of the electron saturation current occurs due to the fact that the plasma ions do not evacuate instantaneously (recall that $v_b \gg c_s$). The duration of the overshoot corresponds to the time ($\tau_s \approx r_s/c_s \approx 0.15\ \mu$s) taken by plasma ions to move with the sound speed ($c_s \approx 2 \times 10^5$ cm/s) across the sheath region ($r_s \approx 5\lambda_D \approx 0.3$ mm). Before plasma ions can move, the positive probe potential strongly penetrates into the plasma and in turn influences the ion beam. While the beam front has propagated toward the probe through a potential-free plasma, the subsequent part of the beam propagates through a decelerating potential. Hence, the ion beam disruption occurs due to the time-of-flight effect and the beam density inside the sheath decreases leading the sheath back to its initial unperturbed state. The above mentioned process should continue for the subsequent part of the beam. Let us notice that the detailed analysis of the instability implies rather complicated dynamics of plasma particles, which require further theoretical investigations.

The above model deals with the planar sheath geometry. If the sheath expansion changes the planar sheath to a spherical one, it may induce additional effects. Indeed, the spherical sheath deflects the ion beam sideways which may cause the sheath to recede and to create an oscillation.

In conclusion, a new kind of low-frequency sheath instability has been observed in a non-Maxwellian plasma containing a group of energetic ions produced by resonant absorption of a short microwave pulse. The instability with its characteristic frequency lower than the ion-plasma frequency occurs in the sheath of a positively biased electrode irradiated by an energetic ion flux due to the sheath collapse and consequent disruption of the ion flux. The observed phenomena can occur in both space and laboratory plasmas with non-Maxwellian ion distributions and could be used as a sensitive diagnostic of the energetic ion component in a plasma.

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